

## PAPER 4.7

## BALLOON INFRARED ASTRONOMY PLATFORM (BIRAP)

M.E. Greeb

G.A. True

Ball Brothers Research Corporation

## ABSTRACT

Our goal was to develop a balloon borne attitude control system for infrared astronomy studies using flight proven hardware and/or techniques as much as possible. The resulting BIRAP system is the realization of that goal. BIRAP will be used to study sources that emit little or no energy in the visible spectrum. Existing technology in tracking sensors does not permit the direct pointing method. Development of a sensor for direct sensing of the IR sources was discarded immediately as nonfeasible from a cost consideration. The use of existing technology and hardware design, therefore, became the challenge for the BIRAP development. The BIRAP uses "electronic gimbaling" for the offset pointing which eliminates a set of mechanical gimbals. Guide stars with visual magnitudes as low as +6 are used for fine tracking assuring that all areas of the sky can be covered. The BIRAP control concept uses a closed loop system in the airborne equipment with automatic update through a command link that can be operated either manually or automatically by a ground based computer. The first flight of this unique platform is scheduled in mid 1974.

## INTRODUCTION

Observation of astronomical targets emitting little or no energy in the visible spectrum poses several unique problems for the attitude controller. The state of the art in infrared sensors makes direct sensing of the IR source infeasible. In fact the size and shape of many of the IR sources themselves make precise direct pointing difficult even if an IR sensor was available. We chose to sense a visible star and offset the IR instrument to the target of interest as an alternate to direct sensing for BIRAP.

Because it has the basic stellar acquisition and pointing capability, The Balloon Astral Pointing System (BAPS) became the natural baseline for the BIRAP design. BAPS was developed for NASA/MSC, Houston, Texas, and has been flown successful several times from Palestine, Texas.

The BAPS system has been described previously by Gibson et al (1972) and Guthals et al (1973). Both of these papers are referenced several times in this paper.

The primary differences between BAPS and BIRAP are the offset pointing requirement, the IR Telescope interface differences and the operational aspects of the balloon launch. All of the

differences are minor in nature but are necessary for the BIRAP missions. Compatibility to European as well as U.S. launch sites was a major requirement for the BIRAP configuration.

The switch of star trackers is the most significant change for BIRAP. The BAPS tracker was replaced by an existing star tracker design currently being used in the SASS-C spacecraft. The BIRAP tracker permits tracking dimmer stars and provides greater offset accuracy capability than the BAPS tracker.

The two axis gimbal configuration is actually a third generation design. The same basic gimbal configuration was used in the Balloon Borne Solar Pointer designed and built for the Air Force Cambridge Research Laboratories (AFCRL). This pointer is described by Toolin et al (1973), and Greeb (1965). The stellar version of that system (BAPS) is an outgrowth of the BBSP. Both the BAPS and BIRAP systems are by necessity more complex than the BBSP, primarily because the acquisition of a stellar target is more difficult than acquiring the sun and more than one target is normally observed during each stellar mission.

Addition capability has been incorporated into the BIRAP system to allow introduction of offset commands, permit automatic ground computer update of the offset signals through the command link, compensate for instrument cryogen loss and measure the payload pendulation.

A brief description of each of the major subassemblies is given in a later section. The emphasis in this paper will be on the concepts, problems and hardware unique to BIRAP. Since control electronics and command system for BAPS and BIRAP are nearly identical and an excellent description of the BAPS system is contained in papers by Gibson et al (1972) and Guthals et al (1973), we will not address these areas in great detail. However, a sufficient general description has been included to allow the reader to visualize both the operation and physical appearance of the system.

## SYSTEM CONCEPT AND OPERATION

The basic purpose of the BIRAP system is to point a telescope towards an IR source with a design goal accuracy of  $\pm 30$  seconds. A summary of the major BIRAP specifications is listed in Table 1. To appreciate the fine sensor requirement and to understand the offset pointing method, it is necessary to understand the basic gimbal set that is used. The system shown pictorially in Figure 1, and as a two view sketch in Figure 2 is made up of the landing platform and the pointed section. The upper half of the unit including the tubular structure makes up the pointed section. This entire section is fastened to a suspension tube. The suspension tube serves as the couple between the balloon and the landing platform, and the azimuth shaft for the pointed section. When the payload is properly balanced, the action of gravity holds the suspension tube parallel with local

Table 1  
BIRAP SYSTEM CAPABILITY

<u>Parameter</u>	<u>Capability</u>
<u>POINTING ACCURACY</u>	
Acquisition - Elevation Axis	$\pm 0.5^\circ$
- Azimuth Axis	$\pm 2.0^\circ$
Fine Pointing Accuracy (Neglecting Penulous Motion)	
Maximum	$\pm 1 \text{ min R.S.S.}$
<u>ACQUISITION TIME (Slew Rate)</u>	
Maximum Time from Initiation to On Target Pointing ( $90^\circ$ angle change)	<300 sec
<u>TARGET RESTRAINTS</u>	
Number of Objects to be Observed	Limited only by observation time
Guide Star Magnitudes	+6 to +2
Maximum angle between guide star and experiment target	$5^\circ$
<u>SCAN RATE</u>	$10 \text{ min/min}$
<u>ASCENT AND DESCENT INSTRUMENT POSITION</u>	
Azimuth - Ascent	Caged to Landing Platform
- Descent	Uncaged
Elevation	Caged to Horizontal
<u>INTERFACE</u>	
<u>Mechanical</u>	
Maximum Instrument Length	150 cm (59 in.)
Outside Diameter	80 cm (31 in.)
Maximum Instrument Weight	95 kgf (200 lb.)
<u>Electrical</u>	
Commands Available	16 discrete, One 16 bit serial digital word
Power	150 AH
<u>GIMBAL FREEDOM</u>	
Azimuth Axis	Continuous
Elevation (Zenith Angle)	$30^\circ$ to $100^\circ$
<u>TOTAL WEIGHT INCLUDING INSTRUMENT</u>	410 kgf (900 lb.)

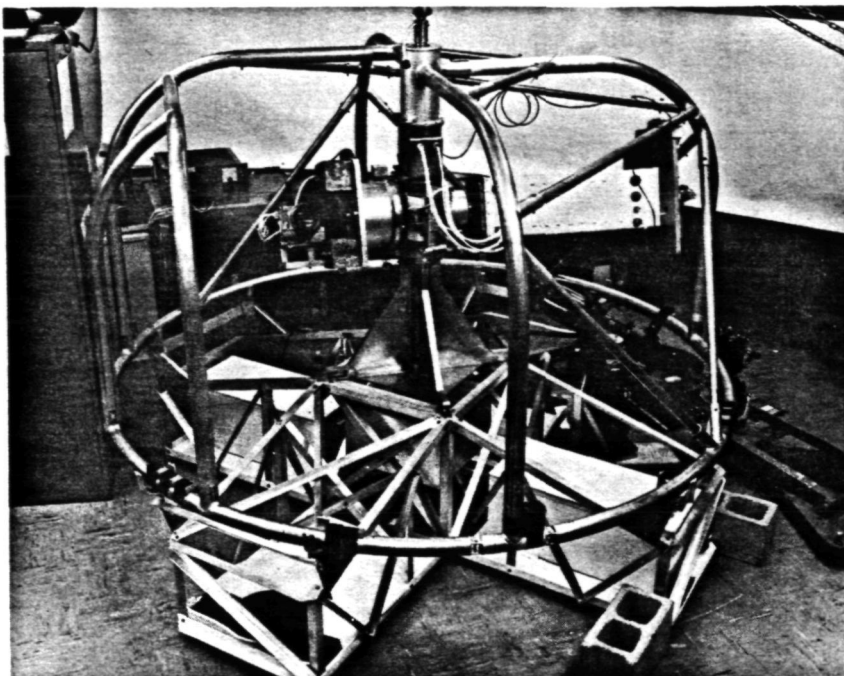


Figure 1 BIRAP System Configuration

vertical. The landing platform provides the inertia for the azimuth servo to react against. The pointed section has unlimited freedom about the suspension tube (azimuth axis) as it rotates in a plane perpendicular to local vertical. The IR Telescope and the star tracker are mounted to another axle attached to the pointed section. The telescope and the star tracker are free to rotate about this axle (which is defined to be the elevation axis) in a reference plane that is perpendicular to the azimuth plane. During initial acquisition, the pointed section is rotated about the azimuth axes until the target star lies in the reference plane. The proper rotation about the elevation axis will then align the telescope and star tracker optical axes toward the target star. Initial acquisition of the target star is complete when the center of the star tracker FOV is pointed directly at the star. This initial acquisition is accomplished to an accuracy of  $\pm 2^\circ$  in azimuth using the earth's magnetic field as a reference. The elevation acquisition is accomplished to within  $\pm 0.5^\circ$  using a position potentiometer mounted to the elevation axle.

The star tracker mount is designed so that the center of the star tracker field of view is aligned to the optical bore-sight axis of the IR Telescope. Therefore, during the initial



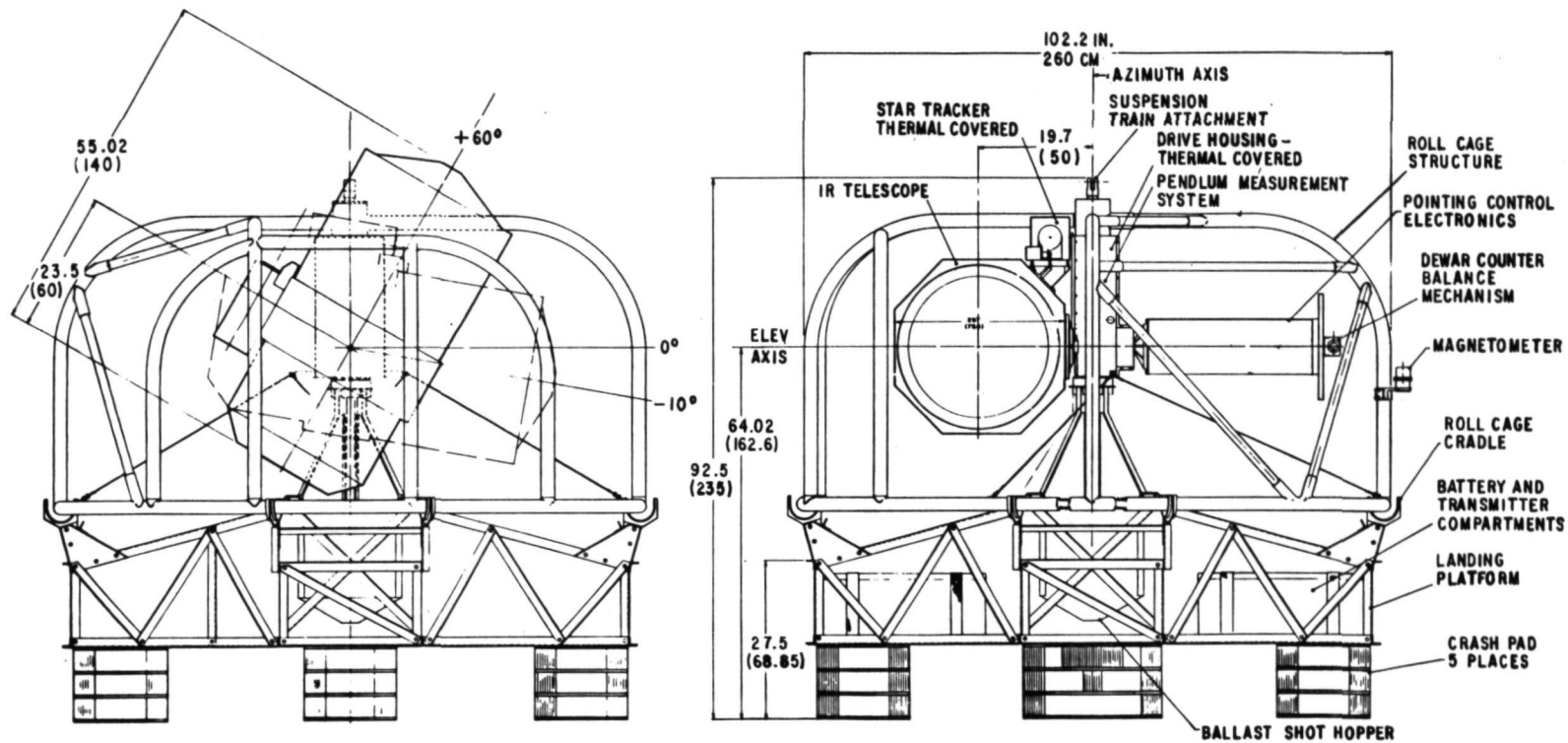


Figure 2 BIRAP Layout Drawing

acquisition both the tracker and the IR Telescope are pointing at the target star. Offset signals are introduced to orient the experiment telescope towards the IR source after the star tracker is allowed to acquire the target star and control has been switched from the magnetometer and elevation potentiometer to the tracker.

We chose the "electronic gimbaling" method to offset the star tracker to avoid another set of mechanical gimbals. Electronic gimbaling is accomplished by simply inserting electrical bias signals into one or both of the servo control loops. Error signals are then required from the star tracker to satisfy the servo null condition. The control system, therefore, rotates about each of the gimbals until the tracker output error signals are equal and opposite in sign from the input bias signals.

In order for the IR Telescope to be pointed at the desired IR source, both the target star and the IR source must be in the star tracker FOV. The BIRAP tracker fits the requirement very well since it has a minimum 8° square FOV and can track stars as dim as +6 magnitude. This combination assures that at any launch site at least one target star will appear in the tracker FOV regardless of the position of the IR source in the celestial sphere.

Two very important considerations were addressed during the feasibility study of this 2 axis, single star tracker approach for BIRAP. They were the effects of payload pendulous motion, and the apparent rotation of the IR source about the target star during long time exposures.

The offset error due to pendulous motion grows to a maximum when that motion occurs in a plane which is parallel to the elevation axis. The pendulation will result in a roll motion about the star tracker line of sight. The roll motion results in a scanning motion of the IR Telescope across the IR source. For small pendulous motion the error signal can be shown to be as follows:

$$\Delta\theta_E = \theta_P \frac{\sin \beta}{\cos \theta_T}$$

where

$\Delta\theta_E$  is offset error

$\theta_P$  is pendulous amplitude of oscillation

$\beta$  is the offset angle

$\theta_T$  is the elevation angle

Our information on pendulation after the payload reaches float altitude indicates a maximum excursion of less than ±10 arc minutes; therefore, the largest error due to pendular motion with a zenith angle of 30° and offset angle of 5° is 1.5 minutes.

Since the BIRAP gimbals are tied to local vertical and local horizontal the apparent movement of the stars during a long

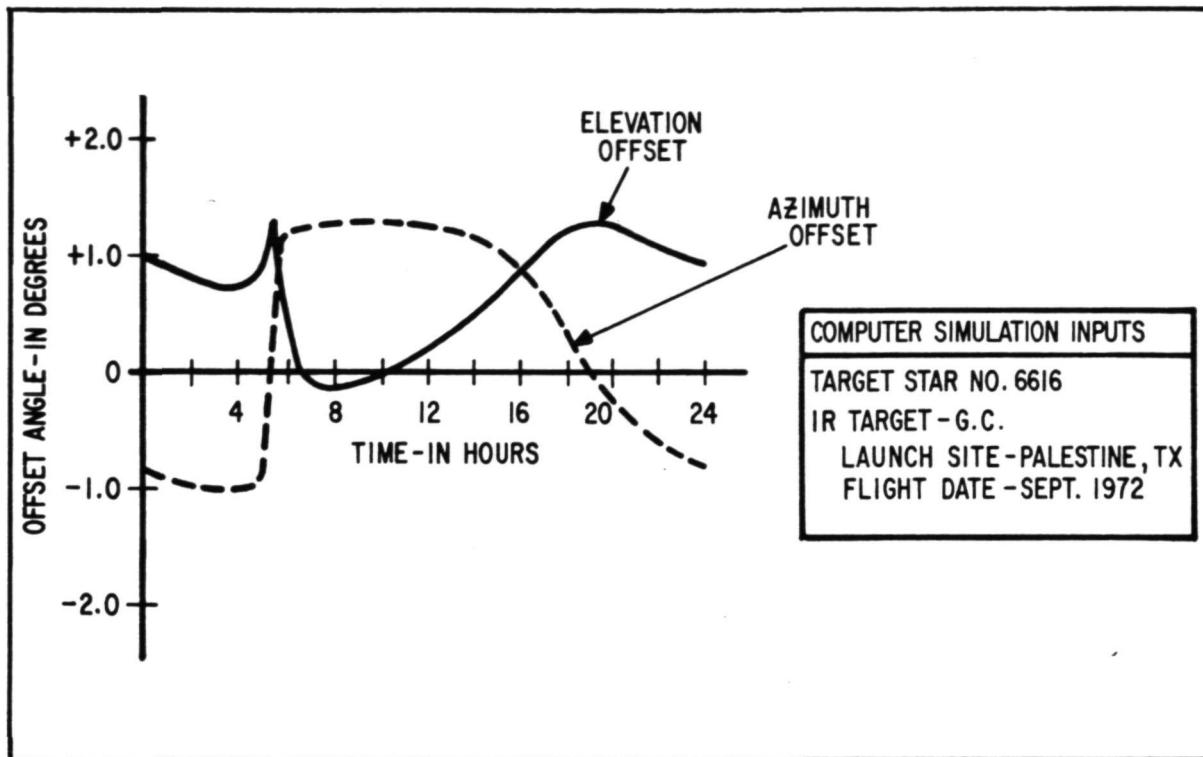


Figure 3 Offset Angles Required to Point at Galactic Center

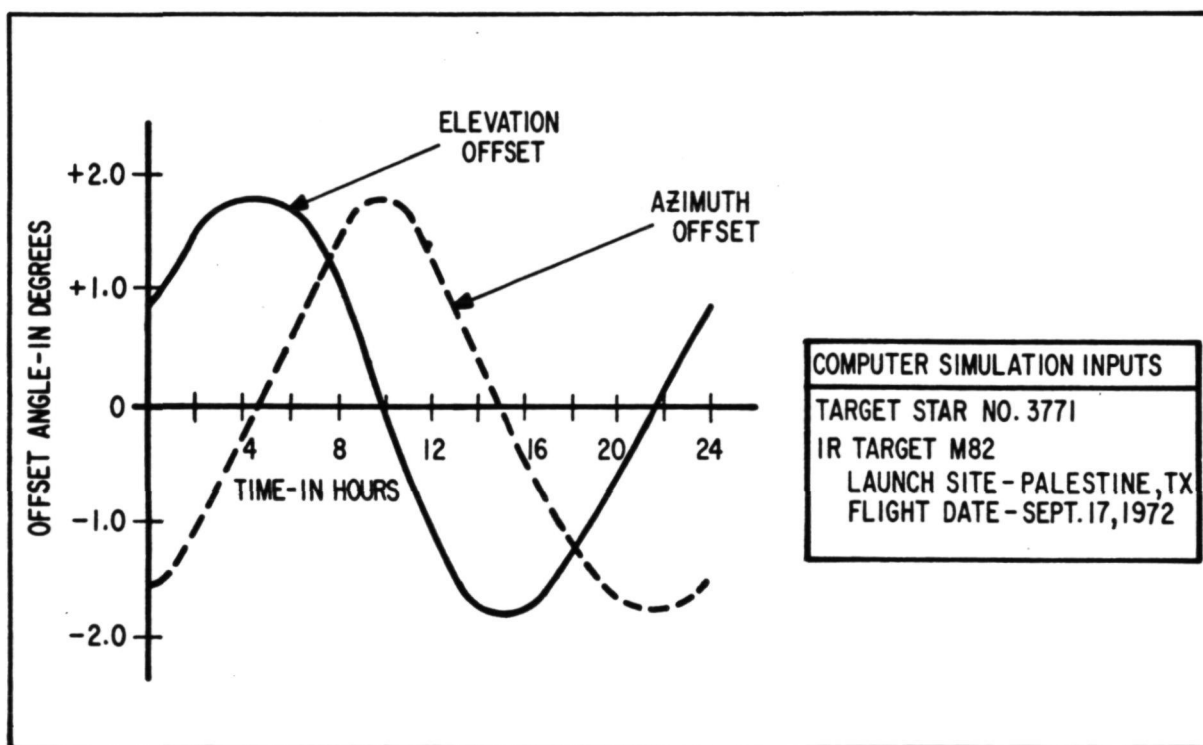


Figure 4 Offset Angles Required to Point at M82

observation time is essentially the same as our own visual observation. If we choose any guide star as a reference and then observe another star with respect to the guide star, the second star will appear to rotate around the guide star once every 24 hours. It is this apparent rotation of the IR source with respect to the target star over a given time interval that is of concern for the BIRAP offset pointing concept. This motion required that the offset angle we command into the star tracker must be continuously updated in order to keep the instrument pointed at the IR source. The rate of change of the two offset angles can be shown to be a function of earth rate, the latitude at which they are observed and the declination angle of the reference target. Figures 3 and 4 depict the change in offset angle required to keep the IR Telescope pointed toward the Galaxitic Center (G.C.) and M82 using star No. 6616 and 3771 respectively as target stars. The computer program from which this data was obtained assumes the payload remains at the latitude and longitude of the Palestine, Texas launch site for the entire 24 hour period. For the launch day shown, the BIRAP restriction to night time pointing would have limited observation of the G.C. from sunset to approximately midnight, the approximate time when the G.C. falls below the earth's horizon. M82 could have been tracked any time during the night. Figures 3 and 4 indicate the offset angle requirement for the entire 24 hour period, ignoring the fact that it is daytime or that the targets might be occulted by the earth or the balloon.

The BIRAP Command System contains the interface necessary to allow automatic offset update using a ground based computer.

During the flight the BIRAP system has four modes of operations, stow, acquisition, fine and offset track. Each mode is initiated by command from the ground.

In the electrical stow mode both of the axes are electrically caged to their respective potentiometers. Both the azimuth and elevation axes will be mechanically locked for ascent. Release is by squib activated pin pullers. The elevation axis will be relatched for parachute recovery. The acquisition, fine and offset modes have been described previously and are discussed in much greater detail in the BAPS papers referenced previously.

#### SYSTEMS DETAILS

Several subtle but important changes were made to the BAPS mechanical design to adapt the basic gimbal, roll cage and landing platform concept to the BIRAP requirements. The physical appearance of the two systems are quite similar to the casual observer. As shown in Figure 2 the system consists of two major sections, a landing platform and a pointed platform section. The pointed platform section is very similar to BAPS. It consists of the suspension tube, drive case and roll cage. The

drive case, depicted in Figure 5 is nearly identical to BAPS. It contains the bearings drive motors and position potentiometers for both the azimuth and elevation gimbals. It also houses the azimuth slip rings and the secant potentiometers used to keep the azimuth servo loop gain constant. The entire drive case is mounted to the suspension tube by the two azimuth gimbal bearings.

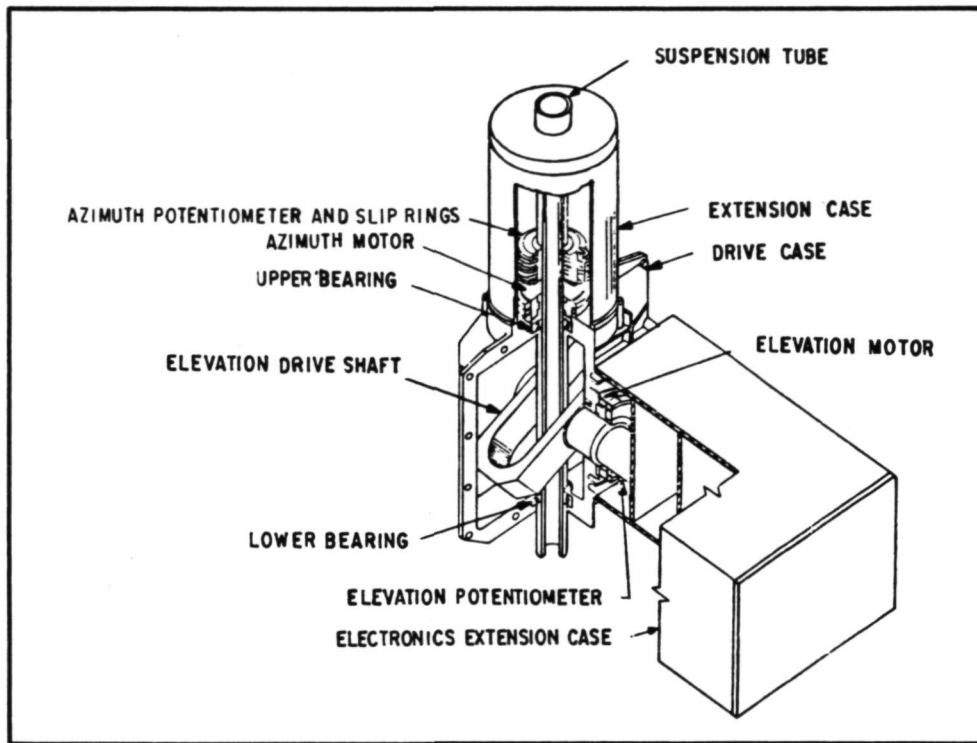


Figure 5 Pointing Control Drive Assembly Details

The elevation shaft is also contained in the drive case. It uses the BAPS yoke configuration shown in Figure 5 to allow the suspension tube to pass through the geometric center of the elevation shaft to the landing platform. The rest of the elevation shaft has been redesigned for BIRAP to accommodate the heavier instrument weight and to improve the bearing loading due to the moments encountered during landing. In BAPS, only the instrument was fastened to the elevation shaft. This caused a large bending moment at the bearing interfaces because of the cantilever effect. Calculations of the bending moments and bearing loading indicate the bending moments are improved considerably if an equivalent weight is added to the shaft on the side opposite the instrument. Even though the total weight on the elevation bearings doubles the increase in friction is negligible.

so the servo performance is very nearly the same. The additional weight was provided by adding a flange to the other end of the elevation shaft and attaching the electronics assembly to it. This approach retained the balance required to keep the suspension tube vertical, improved the bending moment problem and reduces the problem of making electrical connections across the rotating joint between the instrument and the electronics box.

The roll cage, as its name implies, is added to provide protection for the instrument gimbals and electronics if the payload should roll over during landing. The roll cage configuration is similar to the one used for BAPS but it has been reduced in size for easier transport and has been modified to accommodate the wider FOV of the instrument and the greater elevation angle freedom required by the BIRAP system.

The BIRAP landing platform configuration is also similar to BAPS, but it has been scaled down, again for convenience of handling and shipping. The platform is designed to withstand a descent load factor of 15 g's and a ground-traversing load of 10 g's caused by high ground winds and high lateral drift. The crash pads are fabricated from vertical impregnated paper honeycomb panels and columns. They have been tested and exposed to actual flight descent velocities of up to 6 meters/sec (20 fps) and deceleration of 15 g's and with drift velocities up to 10 meters/sec (33 fps).

The star tracker is mounted directly to the IR Telescope house to minimize the alignment changes with temperature, etc. Special mounting feet were developed to thermally isolate the star tracker from the cold environment of the liquid nitrogen cooled IR Telescope. A special insulated and heated housing is also provided for the star tracker.

To avoid excessive heating in the gimbal drive motors, the payload must be very well balanced, particularly about the elevation drive shaft. The IR instrument requires the use of a liquid nitrogen dewar which unfortunately cannot be mounted on the center of rotation of the elevation shaft. The instrument balance assembly has been added to the system to automatically compensate for the loss in cryogenic liquid. Since the electronics box rotates with the IR instrument it was more practical to add the balance unit to the end of the electronics box because the thermal interface problem is avoided and connections to the sensing electronics is much easier.

The control electronics for the system are essentially the same as used in BAPS except for the addition of the instrument balance circuitry, the pendulation measuring gear, and the offset signal summing required for BIRAP. The sensing for the balance system is accomplished by sampling the integrator output in the elevation servo loop. When this output exceeds a steady state preset value, the motor in the balance unit is activated to drive the weight until the integrator output is reduced below the threshold point. The polarity of the integrator output deter-



mines the direction of the motor drive.

Two digital-to-analog converters provide the offset signals to the control system. These converters are loaded with data via the command system. The outputs from the converters are introduced directly into the servo control loop to produce the offset.

The mechanization of the magnetometer loop and the potentiometer loop for acquisition and the servo analysis for all the modes of operation are discussed quite well by Guthals et al (1973) and Gibson et al (1972) therefore they will not be repeated here. It will suffice to say that with the exception of the offset inputs, the changes required for BIRAP were minimal. A system functional diagram of BIRAP is shown in Figure 6. Additional packaging design was done for BIRAP to put the electronics on printed circuit boards instead of the terminal layout method used for the electronics on BAPS. This change simplified the fabrication and increased the reliability of the system.

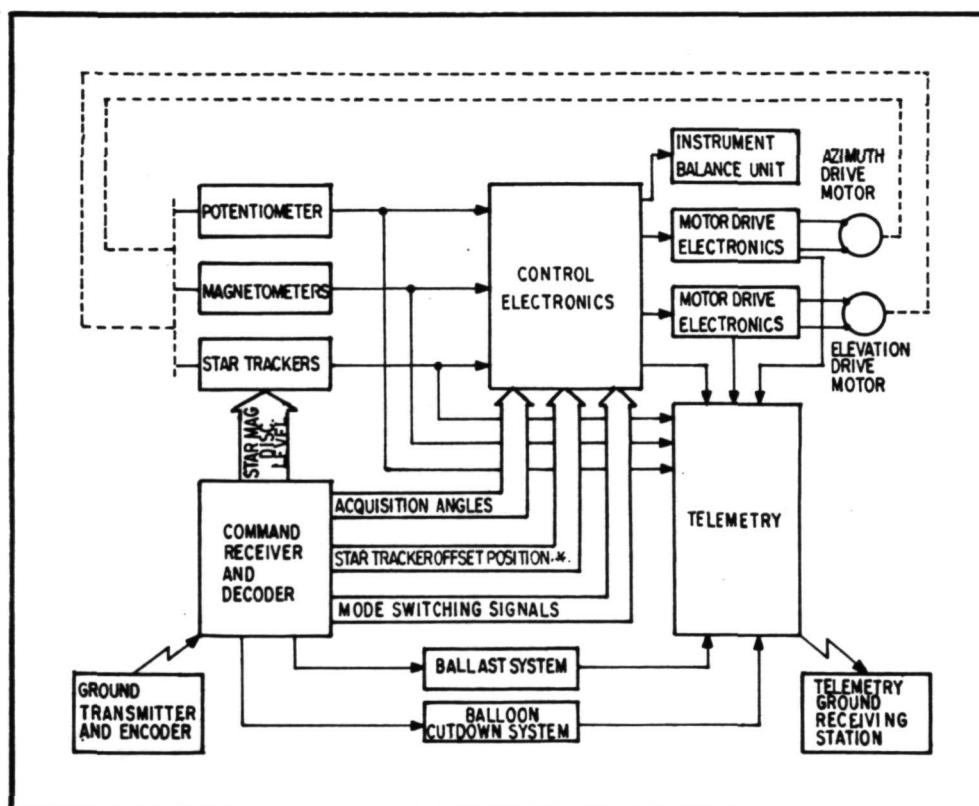


Figure 6 BIRAP System Functional Diagram

An integrating gyro package has been added to BIRAP to measure the pendulous motion which causes movement of the IR instrument that is not corrected by the control system. The intent is to monitor this signal and add that variable into the data reduction. The signal will also be monitored during flight so that if the pendulous motion becomes too large for good data retrieval during a particular measurement, that data can be ignored or a new measurement can be made. The system has a minimum resolution of one arc minute peak pendular swing at a frequency of 5 Hz or less.

The command system used on BIRAP is nearly identical to that used on BAPS. It is a digital coding system with the capability of 16 discrettes (output command pulses) and one 16-bit serial digital word that can be processed by the BIRAP electronics and by the experiment. Included in the command system is a control panel, a ground based encoder, and the command receiver and decoder which mounts in the payload. The ground equipment interfaces with a DR11-A interface unit (customer supplied). The interface unit permits the flight system to accept data directly from a PDP-11 digital computer. The ground equipment allows the offset angle to be updated automatically using the computer. Two sixteen-bit words, four bits for address, twelve for actual data are contained in each two axis command. Each command can be sent at a rate of 30 commands per minute. This command rate is based on a 25 bps clock rate from a 50 Hz line. For a 60 Hz line the rate is 30 bps with a command rate of 37 commands per minute. Manual control is used for mode changes and multiple target acquisition. Backup manual offset command control may also be used.

The two primary sensors used by the control system are the two axis magnetometer and the star tracker. The two axis magnetometer is used to sense the magnetic field direction in the azimuth plane. The electronics uses the output of the two magnetometers and a command input signal to produce an output position angle reference for the azimuth axis. The magnetometer sensor assembly is mounted on the roll cage to isolate it from elements that tend to distort the earth's magnetic field.

The star tracker shown in Figure 7 provides the input signals to the control electronics during the fine and offset pointing modes of operation. It has a total field of view of  $8^\circ$  by  $8^\circ$  square during star acquisition and approximately  $10^\circ$  diameter circular during fine pointing and offset modes. It can acquire and track stars with magnitudes from +2 to +6. The combination assures that there will be at least one target star available regardless of what part of the celestial sphere the star tracker is pointed to. There are some areas of the sky where more than one target star will be visible within the  $8^\circ$  FOV of the star tracker. To be assured that the right star is acquired four different star magnitude discrimination levels (+6, +5, +4, +3) can be set into the star tracker through the command system. The tracker will track only stars that are brighter than or equal to the command level.

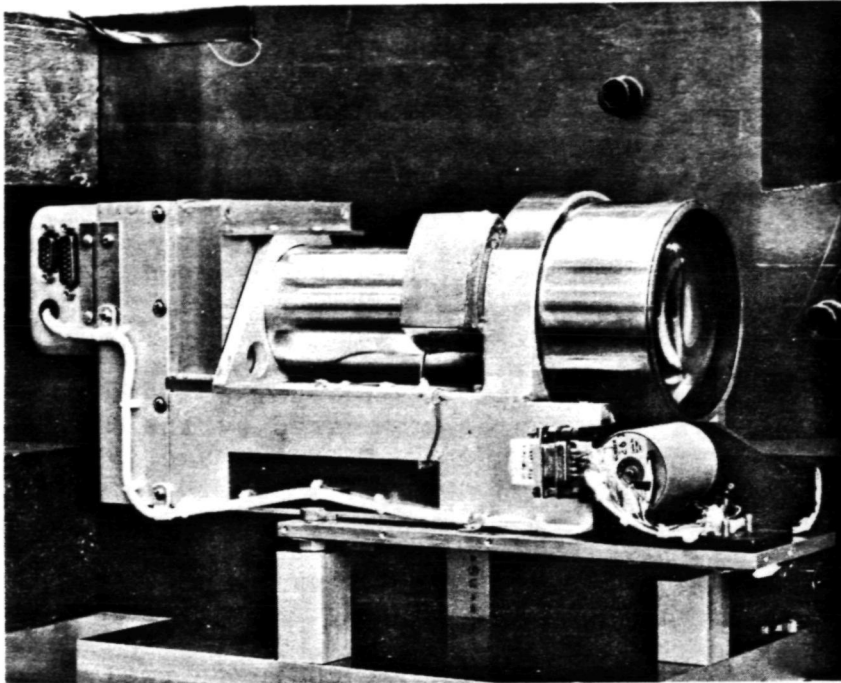


Figure 7 BIRAP Star Tracker

The "initiate search" control command capability of the BIRAP tracker makes it possible to verify that the proper guide star has been acquired if more than one guide star falls within the FOV. The tracker will acquire and track the first star it finds over the threshold set. When the "initiate search" command is given, the tracker will continue through the remaining search pattern and lock onto the next star. By comparing the output angle differences between the two stars, one can verify that the tracker is directed toward the correct star. By varying the magnitude discrimination level, a complete star map can be made to determine the number of stars of the various magnitudes are in the FOV.

The star tracker output stability for the entire range of environments is better than  $\pm 1$  arc min. The drift is predictable and repeatable within  $\pm 20$  arc sec over its entire field of view for variations in operating temperature, star magnitude, star color temperature and magnetic field variations.

The tracker also contains a bright target detector which automatically closes a shutter to protect the star tracker if a target of -10 magnitude or brighter approaches within  $18 \pm 2$  deg from the tracker null axis.

Another shutter mechanism attached to the front of the star

tracker allows acquisition and tracking of bright stars and planets. The shutter reduces the lens aperture to reduce the total incident light to the lens.

The power for both the BIRAP and the instrument is provided by a battery pack consisting of twenty-six YS-150 silver cadmium cells connected in series. This pack has a nominal output voltage of 28 volts and an output capacity of 150 AH. The battery pack is contained in the landing platform. The power is carried to the pointed section through the azimuth slip rings. All of the regulators are contained in the electronics package.

The BIRAP system contains an eight channel FM-FM telemetry system. The voltage controlled oscillators (VCO) and a 90 channel commutator are contained in the electronics box. The output of the VCO mixer is fed through the slip rings to the 250.7 mc transmitter housed in the landing platform. The telemetry antenna is mounted to the bottom of the landing platform.

Thermal analysis performed on BIRAP has determined the surface paints and the amount of insulation and/or heating that is required to keep the various sections at acceptable operating temperatures. Passive temperature control was found to be adequate for the electronics section. Heaters with simple thermostat controls are used in the star tracker and the drive assembly. The battery box is controlled by using freezing fluid passive control.

## CONCLUSIONS

The BIRAP is now completely assembled and is in system performance testing. We are reasonably confident that the system can meet all of the objectives initially established for the system.

## ACKNOWLEDGEMENTS

The BIRAP development program was initiated under contract RIB 63.1232 Dept. VI between Ball Brothers Research Corporation and the Department of Space Research, The University of Groningen, Groningen, The Netherlands.

## REFERENCES

- Gibson, W.C., D.L. Guthals, J.W. Jensen, and J.A. Eccher, 1972. Pointing and Guidance of the BUSS Telescope, presented in a meeting on Instrumentation in Astronomy, Tuscon, Arizona
- Greeb, M.E., 1965. Design and Development of the Balloon Borne Solar Pointer, BBSP200. Final Report by Ball Brothers Research Corporation, Contract AF19(628)-4314.

Guthals, D.L., W.C. Gibson, 1973. Engineering Aspects of a Balloon-Borne Astral Pointing System (BAPS). Proc., Seventh AFCRL Scientific Balloon Symposium, AFCRL-TR-73-0071.

Toolin, R.B., 1973. Observations of Gondola Motions for High Altitude Flight Systems. Proc., Seventh AFCRL Scientific Balloon Symposium, AFCRL-TR-73-0071.

## DISCUSSION SUMMARY — PAPER 4.7

Questions were asked about the cost of the system and the size of the telescope it could hold. The cost was estimated at between \$100,000 and \$150,000. The maximum instrument diameter which can be used with the system is 80 cm and the maximum length is 150 cm. One group is using it for a 60 cm telescope.